

THE APPLICATION OF THE DEEP MIXING METHOD TO DAM AND LEVEE REMEDIATION IN THE UNITED STATES

Dr. Donald A. Bruce, President, Geosystems, L.P., Venetia, PA USA, 724-942-0570,
dabruce@geosystemsbruce.com

ABSTRACT

The paper provides background data on the 84,000 dams and 160,000 km of levees in the U.S. This constitutes an aging portfolio of structures and it is increasingly vulnerable due to deficiencies in design, construction and maintenance, as well as threats from natural sources such as earthquakes, floods, and unstable geology. The three major groups of DMM technologies are reviewed, namely conventional, vertical multi-axis DM; continuous trenching (e.g., TRD); and horizontal axis mixing (e.g., CSM). The four groups of applications of the DMM to dam and levee remediation are described and illustrated with reference to major case histories. The paper concludes that although the remedial market is fundamentally driven by the outcome of risk-based analyses, its rate of growth and volume is a reflection of the comprehensive design guidelines, high quality construction techniques, and intense QA/QC and Verification programs now granted to the dam and levee engineering community by DMM specialists.

SCOPE, CHALLENGES AND APPLICATIONS

According to the National Inventory of Dams (NID), there are about 84,000 dams in the US meeting at least one of the following criteria (Ragon, 2011):

- 1) High hazard classification - loss of one human life is likely if the dam fails,
- 2) Significant hazard classification - possible loss of human life and likely significant property or environmental destruction,
- 3) Low hazard classification – no probable loss of human life and low economic and/or environmental losses, but the dam:
 - Equals or exceeds 8 m in height and exceeds 15 acre-feet in storage,
 - Equals or exceeds 50 acre-feet storage and exceeds 2 m in height.

At least 15,000 other dams have been reported, but which do not meet these criteria. Almost 14,000 dams have been classified as “High Hazard”. It is important to note that only 4% of the dams are Federally owned (e.g., by USACE [United States Army Corps of Engineers], Bureau of Reclamation, and Forest Service) and only a further 2% are owned by public utilities and are therefore subjected to oversight by the Federal Energy Regulatory Commission. Over two thirds are privately owned. Over 87% of the dams are primarily classified as embankments of some form. About 50% were completed between 1950 and 1979, while the median age in the year 2020 is sixty-nine years.

Whereas one can calculate that all the dams in the U.S., if placed end to end, would form a structure about 24,000 kilometers long, *preliminary* estimates put the total length of levees as over 160,000 kilometers. According to Halpin (2010), there are levees in all 50 states, and in addition to the uncertainty regarding their number and extent, there is general ignorance about their current condition and the threat they pose to the population and property they protect. It is clear, however, that tens of millions of people live and work in close proximity to levee systems: originally constructed to protect property, they have often inadvertently increased flood risks by attracting greater development to the flood plain.

Until the 1930's, levee construction was sporadic and unsophisticated without the benefit of systematic engineering or scientific expertise. Levees were considered “simple” structures and so not designed or built to contemporary dam standards. After great devastation and loss of life in the interwar years from the floods in the Mississippi and Ohio River valleys and in Florida, the USACE was directed, at full

Federal expense, to take a more active role in levee design and construction, resulting in the 20,000 kilometers or so of "robust" levee systems now in place. Many of these levees, which make up the backbone of the nation's levee system, are now therefore well over sixty years old and, even when regularly maintained, may not have been brought up to the most recent engineering standards. The balance of the inventory includes municipal, local and agricultural structures.

Dam or levee failure can arise from one or a combination of factors relating to design, construction or maintenance shortcomings on the one hand, and fundamental geological and geotechnical controls on the other hand. In this regard, soluble lithologies immediately underly about 40% of the contiguous United States (Martinez et al., 1998) while there are several regions of extreme seismic activity in the central, south eastern and western states in particular. To these challenges must be added those transients posed by extreme weather events, causing flooding and overtopping, while the problem in the New Orleans area is exacerbated by the ongoing regional settlement of the delta, estimated at 2 – 12 mm per year.

For over 20 years now, portfolios of dams have been subjected to risk-based analyses to help prioritize remedial needs, and to better guide the selection of the remedial measures. The Deep Mixing Methods are being routinely used both for existing structures, and to improve the foundations of new or replacement embankments. The four major categories of application are as follows:

- Seepage cutoff/internal erosion mitigation
- Seismic remediation
- New/replacement foundation strengthening
- Combined buttressing and seepage cutoff for replacement dams – a novel and increasingly attractive concept.

Each of these applications is illustrated in the four case histories described below.

DEEP MIXING METHODOLOGIES

The Deep Mixing Methodologies used in the U.S. are classified in Fig. 1.

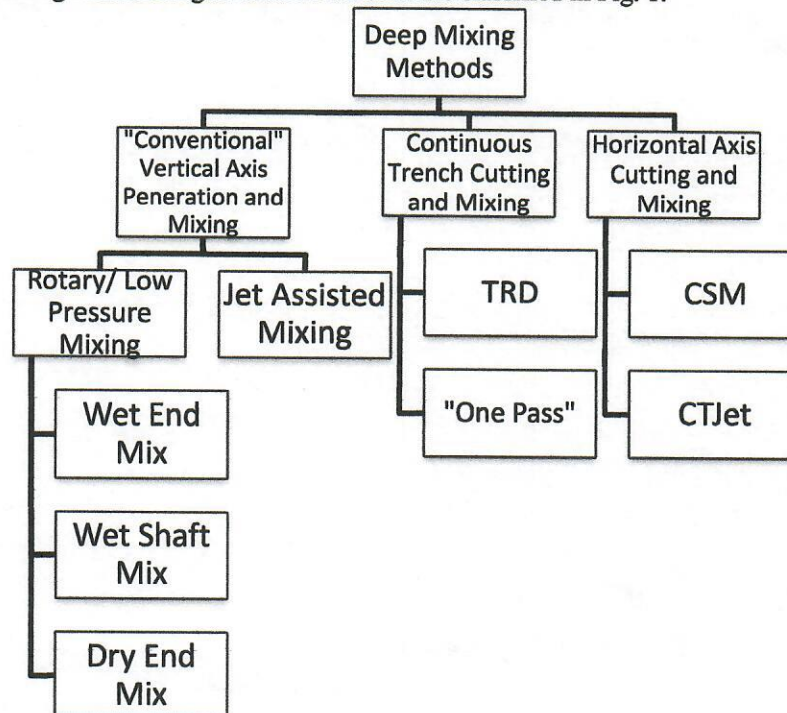


Fig. 1. Classification of DM Methods used in the United States.

Drawing from observations of the dam and levee market since the first application of DMM in 1987, [Table 1](#) provides a simple perspective. Although dry DMM was used on several smaller projects in the New Orleans area in the period 2006 – 2010, all other DMM techniques used for dam and levee remediation have used wet methods (Bruce, 2013). A common thread in all these major dam and levee remediations is the very intense levels of QA/QC and Verification which are applied. These exploit the value of the onboard instrumentation which contemporary models of DMM equipment of all types carry. Thus, there is precise control over the location, depth, width and continuity of the DM elements, as well as their material properties, in-situ.

Table 1. Summary of DMM Usage for dam and levee remediation

APPLICATION	CONVENTIONAL VERTICAL AXIS	CONTINUOUS TRENCHING	HORIZONTAL AXIS
Seepage cutoff	Original method used, remains viable	Very attractive on big projects	Very popular on projects of all sizes
Seismic remediation	Very common	Not applicable	Common
Foundation strengthening	Very common	Not applicable	Common
Cutoff and buttress	Can be used	Can be used	Can be used

ILLUSTRATIVE CASE HISTORIES

Seepage Cutoffs

As indicated in [Table 1](#), conventional vertical multi-axis DMM was the original method of choice, from Jackson Lake Dam, Wyoming (1987) onwards. However, with the technical issues inherent in such cutoffs (e.g. limitations on depth, continuity of the cutoff, productivity) and the introduction of competitive methods like CSM and TRD (and similar types) in 2005 – 2006, the use of conventional vertical axis DMM has somewhat declined in many areas (but not California) in favor of the other DMM methods. This is not, however, to denigrate the older work done after Jackson Lake, (Ryan and Jasperse, 1989), for example at Cushman Dam, Washington, (Yang and Takeshima, 1994), Lockington Dam Ohio, (Walker, 1994), or on the Sacramento, Idaho, and New Orleans levee systems, (Yang, 2013). However, the work done, and still underway at Herbert Hoover Dike, Florida, provides an excellent showcase for the more recent methods, and so is featured in this section.

Lake Okeechobee in southcentral Florida is surrounded by a very heterogeneous levee known as the Herbert Hoover Dike, on which early construction by local farmers first began around 1915 utilizing mostly sand and topsoil (Garbin et al., 2009). Portions of the original embankments were overtopped by hurricane-induced surges in 1926 and 1928, resulting in the loss of over 2,500 lives. As a result, about 120 km of levee were reconstructed by the USACE between 1932 and 1938. A major hurricane in 1947 highlighted the need for additional flood protection, and the current dike system for Lake Okeechobee was completed in the late 1960s. The system now consists of about 220 km of levee with nineteen culverts, hurricane gates and other water control structures. Lake Okeechobee has become the third largest freshwater lake in the continental United States, draining to the ocean through the Everglades. The levee crest is typically at around elevation + 11 m, and the lake is normally at elevation + 3 to 4 m. However, as constructed, sections of the levee are prone to instability due to seepage and piping, in particular when lake levels increase beyond certain elevations due to surge caused by severe weather (hurricanes). Therefore, the USACE designed a cutoff wall constructed progressively in prioritized “reaches” each several kilometers long to mitigate piping concerns and ensure dike stability during extreme weather events, Fig. 2.

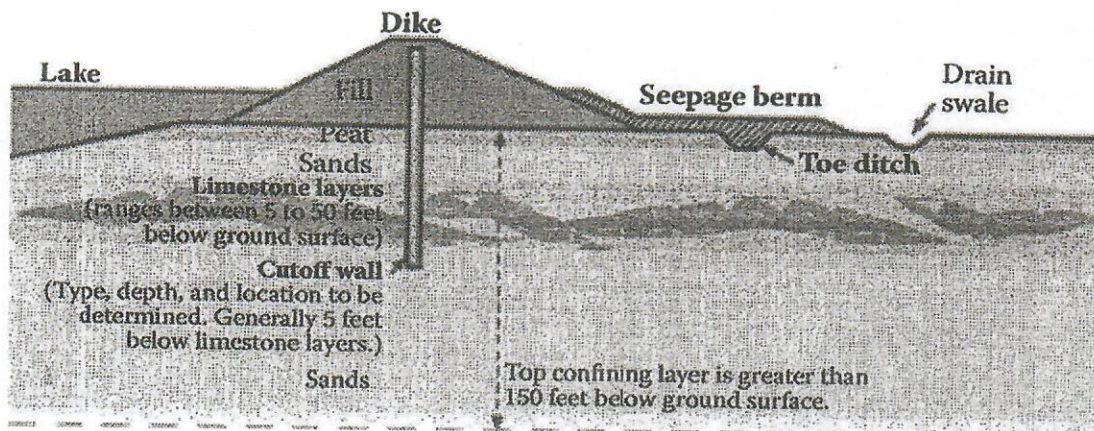


Fig. 2. Schematic of cutoff wall and seepage berm concept, Herbert Hoover Dike, Florida (U.S. Army Corps of Engineers, <http://www.saj.usace.army.mil/Divisions/Everglades/Branches/HHDProject/HHD.htm>, 2007.)

Given the scale of the project (Phase 1 was over 32 km long, and Phase 2, currently underway, is over 48 km long) and the urgency of the remediation, the USACE managed four major risk elements as follows:

1. **Technology Risk:** Prequalification of three different cutoff wall methods (out of eight proposed, each with very detailed statements of prior experience).
2. **Schedule Risk:** Breaking down the whole project into numerous smaller reaches so permitting simultaneous work in several sections.
3. **Project-Specific Risk:** Each reach was predicated by a 150 m-long Demonstration Section. Production was only permitted after USACE had accepted the Demonstration Section Report. USACE also employed an external consulting group as continuity/oversight over all individual contracts.
4. **Performance Risk:** Use of Performance Based Specifications, but featuring very clear QA/QC and Verification criteria defining:
 - Continuity, and verticality (by analyses of on-board instrumentation)
 - 45 to 90 cm wall thickness;
 - In-situ permeability $\leq 1 \times 10^{-6}$ cm/s (in coreholes at 60 m centers);
 - UCS in the range of 0.7 to 3.5 MPa from cores, at 28 days;
 - Chemical compatibility with groundwater and soil.
 - Homogeneity.

These measures were supported by groups of external DMM specialists, acting as oversight and perspective. Approximately 70 percent of Phase 1 was conducted using TRD and CSM methods, the balance being a Self-Hardening Slurry cutoff constructed by traditional cutoff wall methods i.e., grab and hydromill. The QA/QC program was very intense, with core data being supplemented by testing of "bulk" samples (i.e., taken from the spoils generated at the surface) and deeper "wet grab" samples taken from different elevations of the cutoff prior to initial set. (Garbin et al., 2009). Both contractors elected to use grouts with a high slag content, in addition to bentonite and other admixtures to extend workability and reduce permeability as required. The contractors used different mixes, but it was common to see at least a 3:1 slag to cement ratio, and at least 2% bentonite. Samples continued to gain strength even beyond 200 days age. It was common to take special measures, such as chilling the mixing

water, to combat the very high ambient temperatures over the summer months, so as to ensure the binder was below 94°F upon injection.

Bearing in mind the great heterogeneity of the soils to be mixed, the DM material of the cutoff was found by coring and the use of Optical Televiewers to be extremely homogeneous in appearance and in its engineering properties. In the case of the CSM sections of the cutoff, achieving homogeneity was aided by the contractor's decision to predrill the alignment and remove substantial thicknesses of peat and replace them with controlled quality granular backfill.

Seismic Remediation

Details of the design and construction of the seismic remediation projects undertaken at Sunset North Basin Dam, California, Clemson Upper and Lower Diversion Dams, South Carolina, and San Pablo Dam, California, are provided in Yang (2013). Since then, a similar, massive project has been conducted at Perris Dam, California, (Chen et al., 2015). In each case, multiaxis conventional DMM was used to create treated blocks of soil to intercept potentially liquefiable layers at various depths. Details of the design layout of course vary between the projects, but the scheme adopted for Clemson Dam is typical (Fig. 3). To form the shear walls, 3m long panels of 0.9 m diameter columns were placed at 4.6 m spacings. The transverse shear walls of the cells provide the required resistance to lateral forces induced by an earthquake, whereas the connecting longitudinal wall prevents liquefied sediments from squeezing or flowing between the transverse walls. DMM is usually selected as the preferred option when the construction of a major excavation at the downstream toe of a dam since to remove and replace liquefiable materials would cause unacceptable dam safety conditions. The required strength of the mixed soil depends on many factors but one of the most important is the Area Replacement Ratio, reflected in the layout of the DMM elements. For seismic retrofits, it is not uncommon for this ratio to be 40 – 50%. Required strengths are typically 2.5 – 5.0 MPa at 28 days, thereby requiring higher Cement Factors than mixes used for cutoff walls (Yang, 2013).

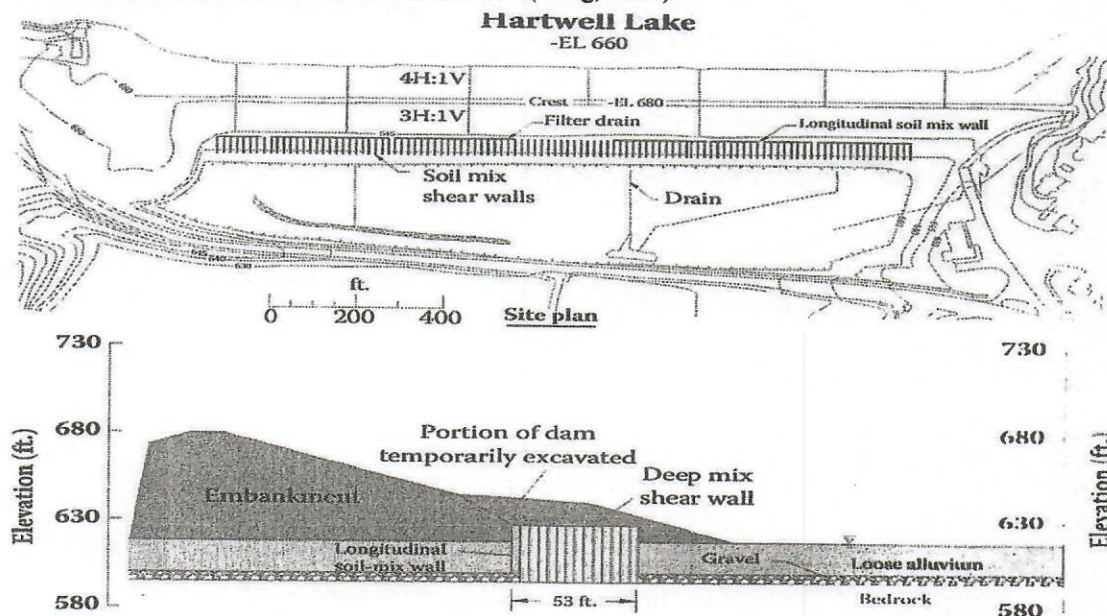


Fig. 3. DMM layout at Clemson Dam, South Carolina. (After Wooten, R.L., and B. Foreman, Proceedings of the 25th Annual United States Society on Dams Conference, 2005; Courtesy of USSD.)

Foundation Strengthening

Throughout the world, one of the most common applications of DMM is to improve foundation conditions under new (or replacement) embankments and levees. Settlements are thereby reduced, and

the bearing capacity of the foundation materials improved. Design procedures have been formalized by many famous authors especially in the Nordic Countries, Western Europe, Japan and the U.S., such as Filz and Templeton (2009), and so the procedures are well established and well known. In the U.S., the most prominent example to date is the work at LPV-111, in New Orleans. This project was the subject of many papers in the 2012 Grouting and Deep Mixing Conference, amongst other venues, and is also detailed in this Conference. (Bruce and Cali, 2020).

As part of the Lake Pontchartrain and Vicinity Hurricane Protection System, the levee enlargement project identified as LPV-111 presented challenges that required innovative approaches in design, contracting, and construction. LPV-111 extends 9 km along the north bank of the Gulf Intracoastal Waterway (GIWW), bordered on both sides by the Bayou Sauvage National Wildlife refuge. This constricted levee construction to the existing right-of-way between these features, and this made DMM the most viable means for reducing cost and schedule.

Subsurface conditions consist of clayey levee fill over soft clays, peat, and organic clays to a depth of about 21.3 m below the crest of the existing levee. Underlying the soft clays are stiff Pleistocene age clays and medium dense sands.

To raise the existing levee by 3.3 m, and meet the more stringent design standards of the Hurricane and Storm Damage Risk Reduction System (HSDRRS), DMM panels were designed to buttress the levee against shear failure and to reduce settlement to a negligible level. (Cooling et al., 2012). Overlapping columns of 1.6 m diameter were installed 20.3 m through the working platform and into the foundation, as shown in Fig. 4. Excess return material, which was a blend of binder and foundation soil, generally fat clay of medium consistency, was used to construct the levee core. The return material, termed Recycled Embankment material (REM), proved to be highly competent levee fill. Over 400,000 cubic meters of spoils were reused in this way, with an average unconfined compressive strength of 0.62 MPa, thus far exceeding the shear strength required in design of 0.03 MPa. Full details were provided by Druss et al., (2012). Using REM proved to be an innovative and excellent business decision that saved significant construction time and cost. Design methodology and use of Early Contractor Involvement (ECI) as the acquisition plan for contract award to accelerate construction are described in Cali et al. (2012). The result was project completion on time, within budget, and to the highest industry standards.

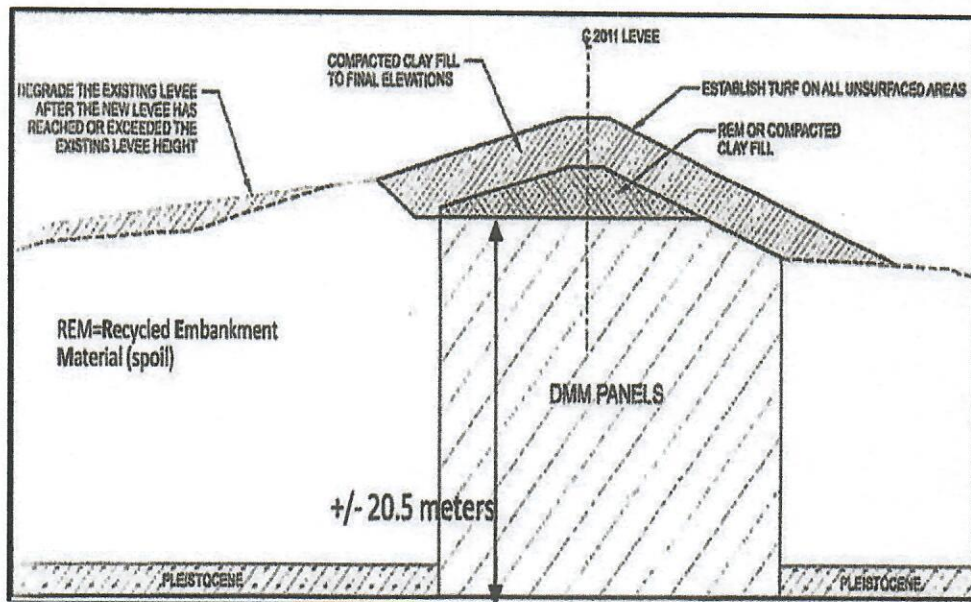


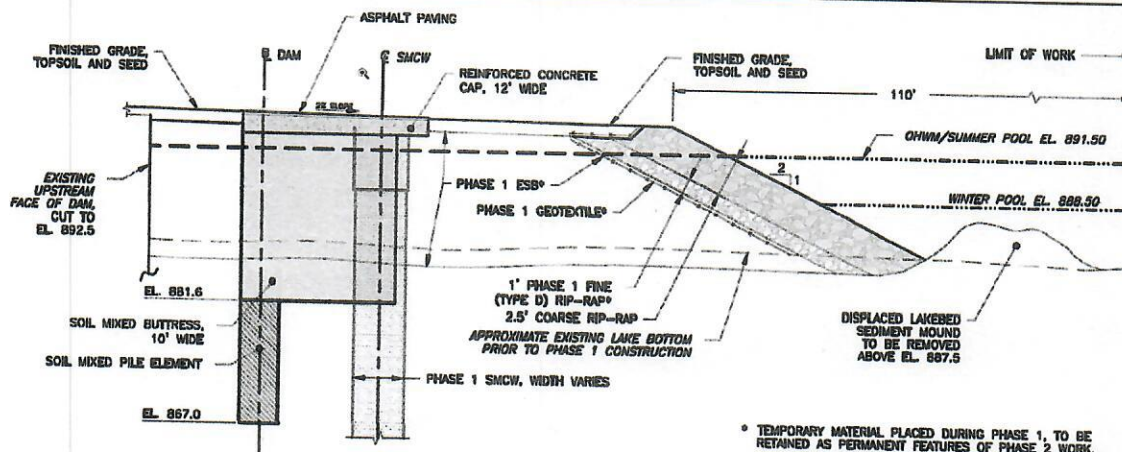
Fig. 4. Final levee design section, Reach 12B (Schmutzler et al., 2012)

The binder used for the project consisted of 25 percent type I/II Portland Cement and 75 percent slag cement, and potable (city) water. For the entire project, over 417,000 tonnes of binder was used at a rate of over 2,000 tonnes per day. Over 454,000 cubic meters of water was used.

Two different DMM technologies were used to treat over 1.4 million cubic meters of foundation soils: 1) Trevi Turbo Mix (TTM), single and double axis, and 2) Fudo Contrivance Innovation Cement Mixing Columns (CI-CMC), as described in Schmutzler et al., (2012). The specifications initially required that the U.C.S. results from nine of the ten specimens from each cored element had to exceed 0.83 MPa, based on a statistical analysis using a coefficient of variation of 0.6 for DMM strength. Actual data from the cores (3% of the 18,000 individual elements) showed that the coefficient of variation was considerably lower and so the strength requirement was safely reduced to 0.69 MPa allowing a reduction in binder factor (Bertero et al., 2012).

Cutoff and Buttress for Replacement Dam

Buckeye Lake, Ohio, was formerly known as Licking Summit Reservoir, and was originally a “feeder” reservoir for the Ohio and Lake Erie Canal System. Upgrading the boundaries of a natural lake by construction of 6.5 km of new clay and shale embankments on the glacial soils lasted from 1825 to 1830. The unfaced upstream slope of the embankment failed in 1832 due to wave action, flooding areas outside the reservoir boundaries. In response, a masonry wall was constructed to protect the upstream face. By the early 1900’s, the canal system was in disarray, and lots on and adjacent to the dam were sold or leased to the public: 370 residences were built into the downstream toe of the embankments. Throughout the ensuing century, tourism increased, and major population centers arose around and downstream of the embankments. A series of engineering studies between 1968 and 2015 concluded that interim risk reduction measures be immediately implemented given the deterioration of the embankment, which included seepage and internal erosion episodes. The first phase of these measures beginning in 2016 included the placement of an embankment stability berm lakeside of the existing dam and a 12 m deep DM wall as a seepage cutoff (Fig. 5). This was conducted by both conventional DMM and by the “One Pass” trenching method and involved 75,000 cubic meters of treatment. Phase 2 involved the construction, by similar DM methods, of a 3 m wide stability buttress, supported by the Phase 1 cutoff and by a deeper row of DM elements. Four thousand passive anchors were installed through the buttress, and into the cutoff to improve structural continuity. The treated volume of the buttress was about 110,000 cubic meters. (Stare and Bruce, 2018)



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Fig. 5. Buckeye Lake Dam Remediation showing the DM buttress and cut-off (Stare and Bruce, 2018).

This innovative design has secured the safety of the embankment against several Potential Failure Modes, and has done so while minimizing disruption to existing homeowners, and the natural

environment. Tourist and recreation amenities have been enhanced while the roadway located above the buttress allows easy access for inspection and maintenance of the new structure. A similar remediation has recently been implemented at Portage Lakes Dam, Ohio, also under the purview of the Ohio Department of Natural Resources.

CLOSURE

The vast and aging portfolio of dams and levees in the United States is increasingly vulnerable to the consequences of inadequacies in design, construction and maintenance, as well as to the threats posed by natural phenomena such as aging, seismicity, floods, and unreliable foundation materials. That there is a market for DM technologies to provide remedial solutions for the various risks these issues have imposed on the dams and levees is unsurprising. However, what is surprising is the size of the market and the rate at which it is growing. This is due to a combination of factors, including the development of comprehensive design guidelines, the availability of well resourced specialty contractors offering a wide range of innovative and reliable construction techniques, and the imposition of intense QA/QC and Verification programs. There seem to be no major obstacles in the path of further expansion of DMM projects in the dam and levee remediation market in the United States.

ACKNOWLEDGEMENT

The assistance of Max Bruce in finalizing this paper is greatly acknowledged

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